

DEVELOPMENT OF HIGH POWER, HIGH PRESSURE, REP-RATE, LIQUID DIELECTRIC SWITCHES

Randy Curry, Kenneth McDonald, Josh Leckbee, Peter Norgard

*University of Missouri-Columbia
Department of Electrical Engineering
Columbia, Missouri 65211*

Ray Cravey, Allen Grimmis

Alpha-Omega Power Technologies
3701 Hawkins Street NE
Albuquerque, New Mexico 87109

Glenn Anderson, Glen Salo

The Boeing Company
P.O. Box 516
St. Louis, MO 63166

Susan Heidger

Wright Patterson Airforce Base
Bldg 137 2310 8th St
Wright Patterson, AFT Ohio 45433

Abstract

The University of Missouri-Columbia (UMC) is developing high power liquid dielectric switches intended to address future high power microwave (HPM) applications. Although requirements encompass a broad parameter space, the initial switch concept focuses on a 250-300kV output switch operated at 100 pps that will be scaled to 1MV. Failure to clear high electric field regions prior to the next charge cycle results in prefires, thereby limiting the maximum achievable repetition rate. Elevating the operating pressure, hence minimizing the bubble size and temporal properties, has alleviated this problem. This paper presents the design philosophy, modeling, and experimental results obtained from a single shot prototype operated in oil at pressures ranging from atmospheric pressure to greater than 13.8 MPa (2000 psi).

I. Introduction

An investigation has been conducted to characterize the voltage breakdown and the by-product formation in high-pressure flowing oil switches. A switch is required near term that will switch 250kV-1MV and currents on the order of 50kA-250kA, for directed energy applications. Concurrently the switch must have a 50 nanosecond or less rise time and be able to operate at up to 150pps. As shown in Table 1 the switch must be able to transfer up to .5 coulombs/pulse and have an operational lifetime of 10^7 - 10^8 pulses.

Table 1. Switch Requirements

Voltage	250-1000kV
Current	50-250 kA
Risetime	<50 ns
Charge transfer	~0.5 Coulombs/pulse
Jitter	<<50 ns
PRF	50-150 pps
Pulse Width	50ns-500ns
.Lifetime	10^7 - 10^8 pulses

The switch proposed by the University of Missouri-Columbia team is based on a high pressure flowing dielectric switch. In 1992, subnanosecond rise time, kilohertz rep-rate oil switches were built and demonstrated that could operate at up to 290kV at 200pps and at 170kV with a rep-rate of 1000pps. [1] The demonstrated rise time into a 97Ω resistive load was 280ps. The modulator system, which utilized medium pressure oil switches, transferred 50 J per pulse [1]. Since that time repetitive oil switches that could operate at 100-1000pps and transfer multikilojoule energies have remained elusive, and have not been demonstrated.

An initial engineering analysis indicated that two issues needed to be resolved if scaling of flowing dielectric oil switches for transfer of kilojoule pulses were to be realized near term. When a high voltage pulse is applied to a flowing dielectric switch, once the switch breakdown voltage is reached, a streamer is launched and subsequent avalanche ionization and breakdown of the dielectric results [2]. The arc then ionizes the dielectric medium and a gas bubble is formed between the electrodes. At atmospheric pressure the diameter of the bubble expands well beyond the electrode separation distance. Our early calculations indicated that the growth and oscillation period of the gas bubble would limit the operation of the flowing dielectric switch to well below the goal of 100-150pps at transfer energies in excess of a kilojoule. Subsequent growth of the gas bubble and potential formation of microbubbles as the gas bubble collapsed would prevent recovery of the oil switch if voltage were reapplied before the entire volume of oil in the switch could be exchanged. As a result it was obvious that pressurization of the fluid was required to reduce the volume and concurrently the radius of the gas bubble.

In order to establish the efficiency of using pressurized flowing dielectric switches for Directed Energy applications a two-phase program was undertaken with an industrial team; Alpha Omega Power Technologies (AOPT) and The Boeing Company. During phase 1 of the program a single shot, flowing dielectric switch was built and instrumented to evaluate the flow required to sweep the byproducts from the interelectrode gap subsequent to reapplication of voltage, and the effect of

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high pressure flowing dielectrics on bubble size, and growth. In phase 2 of the program an optimized flowing dielectric switch will be installed in a rep-rate test stand to determine the recovery characteristics of the switch. The rep-rate test stand, which is discussed in a separate conference paper, can operate up to 250-300kV, switch 250J-300J per pulse at a continuous rep-rate of 150pps. The test stand has an output impedance of 4.4Ω and produces a 70ns pulse. The test stand is also being built to test recovery of the switch at up to 1000pps.

II. Concept Validation Switch Design

Underwater experiments using explosives have characterized the bubble radius as a function of energy [3]. The experiments utilized depth-charges timed to detonate at various ocean depths [3]. The radius as given in equation (1),

$$R_{bubble} = \left(\frac{3}{4\pi} \frac{E}{P} \right)^{\frac{1}{3}} m \quad (1)$$

is a function of the energy E-joules, and the liquid or background pressure in Pascals. The hydrodynamic equations allow the radius of the bubble formed and the oscillation period of the bubble to be calculated [3]. The experimental equation for the bubble radius calculation is for an unconstrained system in a saturated gas liquid environment [3]. The time scale over which the explosive charge delivers the energy is relatively slow compared to the timescale over which an arc transfers energy to a liquid dielectric. As such equation (1) only predicts the trend in the bubble radius size and not the actual diameter of the bubble constrained between two electrodes.

Subsequent low energy experiments using vapor or gas bubbles formed from injecting charge from a needle electrode into liquids have also verified similar results [4]. Kattan measured the radius and oscillation period of bubbles in hydrocarbon liquids including n-decane, n-pentane, cyclohexane, iso-octane and n-hexane formed from thermal heating of the liquid using charge injection [4]. At pressures below the critical value of the liquid, bubbles were formed and oscillated much like that of bubbles formed by explosive sources [4]. Kattan found that in liquids with high thermal electron mobility that the bubble radius formed was substantially less than that predicted by theory [4]. Moreover, above the critical pressure of the liquid, 2.12-4.04 MPa (308-587 psi) no bubbles were formed by the charge injection [4].

In order to estimate the bubble radius, the losses must first be calculated. The phase 1 concept validation test switch was designed to switch a 100ns, 260-270kV pulse into a 1.6Ω load. The energy per pulse delivered to the load is approximately 1 kJ. A photograph of the AOPT pulse power system is shown in Figure 1. The system consists of a 50ns, 1.6Ω water line pulse charged in 1.1-

1.2 microseconds with a transformer coupled capacitor bank. The water line can be charged to 300kV, although the output switch was replaced with a 1.6Ω resistive load and the CVT switch.

The switch losses were calculated using the Braginskii equation and Martin's formulae for the breakdown field of the liquid and the resistive rise time of the arc [5,6,7]. The calculated breakdown field was found to be 1-1.1 MV/cm for a $t_{effective}=0.5\mu s$. For high pressure dielectrics the breakdown electric field has been found to increase by 20-40% [8]. Kao pulse charged a spark gap test stand containing liquid dielectrics pressurized to 2.41 Mpa (350 psig). The dielectrics included ethyl alcohol, methyl alcohol,



Figure 1. AOPT Concept Validation Switch Test Stand

benzene, and hexane, hydrocarbons [8]. A 25-40% increase in voltage breakdown was found during the experiments [8]. The electrode surface area was approximately 18.75 cm² [8]. In other high pressure water tests an increase in the breakdown field of water gaps was also found [9]. However when the electrode area was increased above 100 cm², the pressure effect disappeared [9]. Thus a conservative estimate of the oil breakdown field of 1.0 – 1.1 MV/cm was used to estimate the switch breakdown field. The 10-90% resistive rise time of the switch was calculated to be 6.0-7.0ns.

Utilizing the calculated breakdown field the resistive losses were bounded using both the Braginskii equation and Martin's formulae. The resistive losses were calculated to be 30-60 joules or 3-6% of the energy to be switched. As shown in Table 2 the bubble radius from atmospheric pressure up to 13.8MPa (2000 psi) will vary from 5.1cm down to 1cm for an energy of 60 J. In reality the bubble radius will be somewhat less for the electrodynamics of the arc's plasma. The gas bubbles formed change dramatically for a constrained system in an unsaturated solution, above the critical pressure for fluids, which typically is in the 2-4 MPa (300-500 psi) range. Kattan also found that the radius of the bubble was less than the theoretical value for many liquids [4]. Thus the radius calculated in Table 2 was, we believe, the worst case condition or the largest bubble radius that would form.

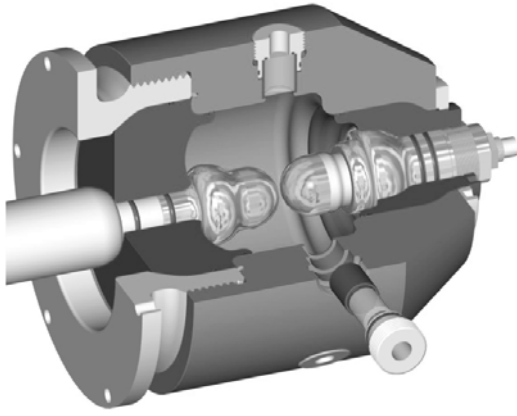


Figure 2. Drawing of the single shot CVT switch

The concept validation switch shown in figure 2 was designed to validate scaling of the flowing liquid dielectric switch to high pressure and to determine the breakdown voltage of small subcentimeter gaps. The switch in figure 2 incorporates adjustable electrodes allowing the electrode separation to be adjusted from 0.1cm up to a centimeter in spacing. Optical viewports were also integrated with the design allowing both the framing and high speed camera diagnostics to be integrated into the test stand. This allowed our team to characterize the bubble formation and byproduct expansion velocity. For a 0.2cm electrode gap the calculated arc inductance of the switch was 3nH (15nH/cm x.2cm). For the 1.6Ω system the 10-90% inductive rise time of the switch is 3.8ns. The calculated 10-90% risetime of the switch was 10-11ns. The electrode material used for the experimental tests was a copper tungsten composite, K33, with an electrode diameter of 3.81cm (1.5 inches). The switch housing and insulator were designed to operate at pressures up to 3000 psig.

Table 2. Bubble Radius and Volume Calculated using Cole's Formula for the Bubble radius

E_{loss}	Pressure	R_{bubble}	Gas Volume
60J	101.3 kPa (14.7 psi)	5.1 cm	565 cm ³
60J	1.38 MPa (200 psi)	2.18 cm	43.4 cm ³
60J	6.89 MPa (1000 psi)	1.27 cm	8.58 cm ³
60J	10.3 MPa (1500 psi)	1.11 cm	5.73 cm ³
60J	13.8 MPa (2000 psi)	1.01 cm	4.32 cm ³

III. Concept Validation Test Results

The concept validation test switch, load resistor and diagnostics were integrated into the AOPT test stand. The diagnostics included two D-dot probes and a Rogowski current monitor. One current monitor was placed on the grounded side of the switch. One D-dot probe was integrated into the water line to monitor the breakdown voltage of the switch. A second D-dot probe was integrated into the oil section adjacent to the high

voltage electrode. The D-dot probe and Rogowski current monitor were calibrated using an external Tektronix 6015 probe and a Pearson Current Monitor at 30kV.

High speed optical diagnostics were used to observe the formation of bubbles and other byproducts. The optical diagnostics consisted of a high speed video camera Kodak Ektapro HG Model 2000 Imager. The other high speed camera, a Hadland Imacon 200 camera, was used to acquire high speed framing photographs of the breakdown process. The high speed framing camera had a capture rate of 1000 or 2000 frames per second. The Imacon camera has a capture rate of 12 images with variable delay times between frames. The exposure time can range between 5ns-5ms for each frame. The electrode area was back-lighted using both fiber optic lights and flashlamps.

A circuit simulation of the integrated switch, transition hardware, and load showed a circuit rise time of approximately 80-100ns due to the transition hardware sections and diagnostic sections installed. The switch 10-90% rise time was calculated to be 10-11ns. Thus the switch was not the limiting factor in the circuit rise time.

Experiments were conducted at atmospheric pressure up to 13.8MPa (2000 psig). The breakdown experiments reported were conducted at a gap spacing of 0.2cm. The voltage breakdown of the 0.2cm electrode gap are shown in Figure 3. Each data point represents the statistical average of ten breakdowns using unconditioned electrodes. The error bars represent one standard deviation for each data set at the test pressure. The curve fit shown is a second order polynomial least squares approximation. The data shown indicates that the breakdown strength increases by 25-30% from atmospheric pressure to 10.3MPa (1500 psig). The breakdown strength then decreases from 10.3 MPa (1500 psig) to 13.8 MPa (2000 psig). We have not yet found an explanation for this phenomenon. After conditioning the electrodes with 45 shots, the voltage breakdown statistical variation decreased to $\pm 6.5\%$.

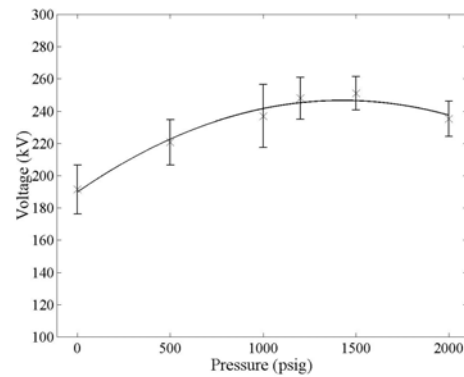


Figure 3. Average breakdown voltage for a .2cm gap with one standard deviation error bars

The gas or vapor bubble formed at atmospheric pressure, 6.89 MPa (1000 psig) and 13.8 MPa (2000 psig)

were photographed with both the high speed video camera and the framing camera. The maximum radius of the bubble exceeded the field of view at atmospheric pressure although one event photographed did allow the oscillation period to be estimated. This oscillation period was approximately 9ms. The theoretical calculations predict an oscillation period of 5-10ms. The gas bubble formed at atmospheric pressure also expanded past the outer diameter of the electrodes. Above the critical pressure of 3.45 MPa (500 psig) microbubbles along with an expanding cloud of carbon particulates were photographed at the high pressure operation. The microbubbles appear to be on the order of 1mm or less in diameter. At pressures from 6.89-13.8 MPa (1000-2000 psig) the microbubbles disappear and are apparently reabsorbed by the undersaturated solution in 20-40ms. For the first 2ms, the expansion radius of the carbon cloud is .7cm with an initial expansion velocity of 7m/s. After 2 ms the expansion velocity slows to less than 12.5cm/s.

IV. Phase II Demonstration Validation Test

We are in the process of designing a 250-300kV demonstration validation switch for continuous 100pps testing. The switch will be integrated with a high pressure test stand. The test stand will incorporate a prototype rep-rate switch that will switch a 250-300J per pulse, 5GW into a 4.4Ω load.

The test stand is being designed to allow flow rate regulation from 0.1 l/s to 2 l/s with rapid adjustment of the electrode spacing and geometries. Both D-dot probes and Rogowski monitors are being integrated into the test stand for measurement of the switch energy losses. The test stand is also being designed to allow 1000pps burst mode operation. This will allow the switch recovery to be measured as a function of the flow rates [11].

V. Conclusion

A prototype concept validation test switch has been designed and tested for single shot operation at up to 300 kV. The breakdown electric field of the switch varied between 1.1-1.25 MV/cm with a statistical variation of $\pm 10\%$ which decreased to $\pm 6.5\%$ after conditioning of the electrodes. The flow characterized from the high-speed photography indicates that the byproducts expand with a modest 12.5cm/s expansion velocity after the first two milliseconds. This upon review indicates that a 300kV high-pressure switch can be designed with a modest flow rate of 1-2 l/s, at 6.89-13.8 MPa (1000-2000 psig).

Concurrently the rise time of such a switch pulse charged in 1-1.2 microseconds will have a rise time of 10-11 nanoseconds or less, and allow kilojoules per pulse to be transferred at 100-200 pps. The technology also appears to be scaleable to the goal of 1 MV and 100 pps operation. A modest 3-7 l/s flow-rates will be required for such a switch.

VI. References

- [1] R. Curry, P D'A.Champney. C, Eichenberger, J Fockler, D. Morton, R. Sears, I Smith, and R. Conrad, "The Development and Testing of Subnanosecond-Rise, Kilohertz Oil Switches for The Generation of High-Frequency Impulses", *IEEE Transactions on Plasma Science*, Vol. 20, No. 3, June 1992
- [2] E. Kuffel, W.S. Zaengl, High Voltage Engineering, Pergamon Press, 1984, Oxford.
- [3] R. H. Cole, Underwater Explosions, Princeton University Press, 1945
- [4] R. Kattan, A. Denat, N. Bonifaci, "Formation of Vapor Bubbles in Non-polar Liquids Initiated by Current Pulses", *IEEE Transactions on Electrical Insulation* Vol. 26, No. 4, August 1991, pp 656-662
- [5] T.W.Hussey, K.J. , J.M. , N.F. Roderick, R.C. Pate, E. K, AFRL, Kirtland AFB, NM; "Dynamics of Nanosecond Spark-Gap Channels", Pulsed Power Conference, 1999. *Digest of Technical Papers., 12th IEEE International*, page(s): 1171-1174 vol.2 Volume: 2, 1999
- [6] T.H. Martin, J.F. Seamen, D.O. Jobe, Sandia National Laboratories, "Energy Losses in Switches", Proc. IEEE 9th International Pulsed Power Conference, Vol. 1, 1993, pp. 463-470
- [7] J.C. Martin, "Solid, Liquid and Gaseous Switches", *Pulsed Power Lecture Series*, Lecture No. 30
- [8] K.C. Kao, J.B. Higham, "The Effects of Hydrostatic Pressure, Temperature, and Voltage Duration on the Electric Strengths of Hydrocarbon Liquids", *Journal of the Electrochemical Society*, Vol. 108, pp. 522-528, 1961.
- [9] Ian Smith, Private Communication, Titan PSD, San Leandro, CA
- [10] J. Leckbee, R. Curry, K. McDonald, R. Cravey, "An Advanced Model of a High Pressure Liquid Dielectric Switch for Directed Energy Applications," IEEE 14th International Pulsed Power Conference, 2003
- [11] P. Norgard, R. Curry, K. McDonald, "A High Pressure, Rep-Rate, Liquid Dielectric Switch Test-Stand", IEEE 14th International Pulsed Power Conference, 2003

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